Connection-oriented networks:

SONET/SDH, ATM, MPLS, and Optical Networks

Michael Devetsikiotis

Professor and Chair

Department of Electrical & Computer Engineering
The University of New Mexico

mdevets@unm.edu

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Acknowledgements

- Many thanks to Professor Harry Perros of Computer Science at NC State for preparing the textbook and many of these slides and material.

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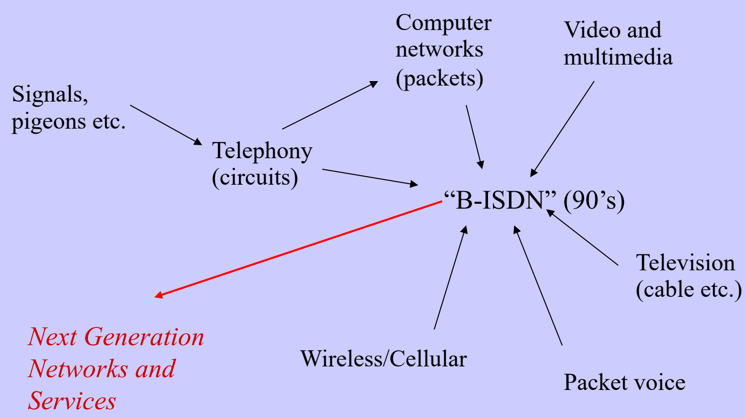
Historical Evolution



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Networking Principles

- *Digitization:*
  - Nyquist
  - Cheaper and more robust
- *Economies of scale:*
  - Cost per bandwidth unit becoming cheaper
  - Fixed costs?
  - The intangible “N^2” factor
- *Network externalities:*
  - Positive if value to user increases with number of users
- *Service integration:*
  - Economies of scope
  - Universal network

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High-Speed Networks: Driving Factors

- *Industry/Technology:*
  - Growth!! (in $s and numbers)
  - Diversity of traffic: ?
  - Deregulation
  - New technologies: QoS, Broadband, 4G, streaming, VoIP, VoD…
- *Society - Problems but also opportunities:*
  - Geography
  - Democracy
  - Access
  - Social Networking
  - But "searching"? Other?
  - Networks not quite as "neutral" as thought…

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Connection-Oriented Networks:

SONET/SDH, ATM, MPLS, and Optical Networks

Michael Devetsikiotis
ECE Department

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Introduction

TOPICS

– Classification of communication systems
– What is a connection?
– Examples of connections
– Motivation for Quality of Service

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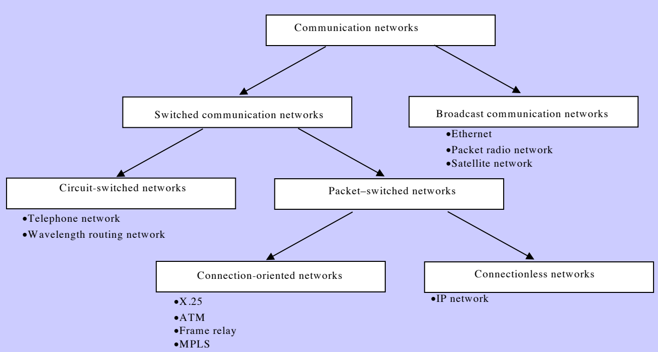
Classification of Communication Networks



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Switched communication networks

- Circuit-switched networks:
  - The telephone network
  - Wavelength routing optical networks
- Packet-switched networks:
  - IP networks
  - ATM
  - Frame Relay
  - MPLS networks
  - 4G and next 5G mobile nets

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Broadcast communication networks

- Examples:
  - packet radio networks
  - satellite networks
  - multi-access Ethernet

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Packet-switched networks

- Connection-oriented networks
  - ATM
  - Frame Relay
  - MPLS
- Connectionless networks
  - IP
  - MPLS?

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Circuit-switched networks

In order for two users to communicate a *circuit* or a *connection* has to be first established by the network. Specifically, the following three phases are involved:

- *circuit establishment*,
- *data transfer*,
- *circuit disconnect*.

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Connection-oriented packet-switched networks

- Circuit switching is a good solution for voice, since it involves exchanging a relatively continuous flow of data.
- However, it is not a good solution for the transmission of *bursty* data

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Connection-oriented packet-switched networks imitate circuit-switched network.

In order for two users to communicate a *virtual circuit* or a *connection* has to be first established by the network. The following three phases are involved:

– *connection establishment*,

– *data transfer*, and

– *connection disconnect*.

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Connectionless packet-switched networks

- In an IP network, a user can send packets to a destination without having to set up a connection first, i.e., without informing the network prior to transmitting them.
- This simplifies the network, as there is no need for a special signaling protocol.

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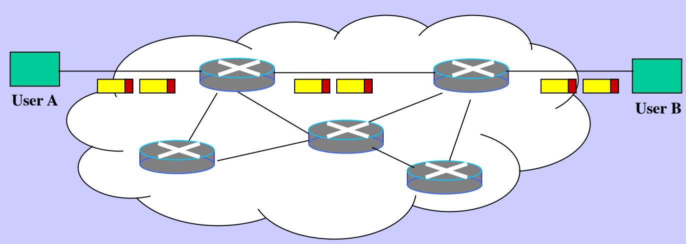
Routing in IP



The routing of a packet through the network is done on a hop-per-hop basis based on the destination IP address carried in the IP packet's header.

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During the ’90s and early 2000s…

- Technological advances:
    - Fiber optics with multiple wavelengths
    - Wireless
    - Satellites
- Traffic demand
    - Audio and video streaming
    - The web (B2B, B2C, C2C)
    - Private networks
    - Peer-to-peer

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- ***Dominant Networking Technologies***
    - *IP networks*
    - *Asynchronous Transfer Mode (ATM, almost gone)*
    - *Frame Relay (gone)*
- ***Emerging Networking Technologies***
    - *Access networks: FTTH, WiMax*
    - *MPLS for the backbone*
    - *3G wireless, 4G, next 5G…*
    - *Optical WDM networks*
    - *LEO satellites*
    - *PON: GPON and other variations*

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Quality of Service

- What do applications require?
  - Video:
  - Voice:
  - Games:
  - Other?
- How does a network "guarantee" quality?
- Trade-offs

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Quality of Service (QoS) in IP

- Typically, an IP router does not offer QoS.
- It cannot distinguish packets belonging to different service classes based on their destination address.
- IP is almost ubiquitous. There has been a lot of interest in introducing QoS in the IP network, and MPLS seems to be the architecture of choice for introducing QoS.

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Example of connections: Telephony

Probably the oldest connection-oriented circuit-switched network is the plain old telephone system (POTS)

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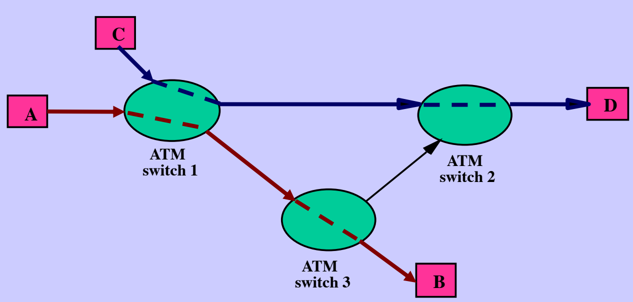
Connections in an ATM Network



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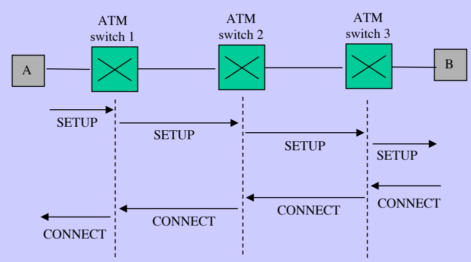
An ATM connection



A bi-directional connection is established using signaling. The connection is associated with a local id number, called a VCI.

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Switching through an ATM switch

- The switching of a cell through an ATM switch is done based on its connection ID number ("VCI").
- A connection is associated with a specific *class of service*.
- An ATM switch can distinguish cells belonging to different service classes, and serve them accordingly in order to provide them with the requested QoS.

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ATM Characteristics

- Unlike IP networks, it was developed from the beginning with a view to carrying voice, video, and data.
- That is, it supports different types of traffic with different requirements for QoS.

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Deployment of ATM

- ATM is not used to connect workstations and PCs in our work environment, since Ethernet dominates this market…
- It is used, however, in the backbone networks of telephony providers, ISPs, and in ADSL (an ADSL modem has a complete ATM card in it!)

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Deployment of ATM

- Backbone of ISPs
- Circuit emulation services
- Video distribution: MPEG2 over ATM
- Residential access networks: ADSL, APONs
- Used in cellular telephony, 3G
- Voice over ATM (trunking and also voice to the user)

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Some market statistics

- ATM equipment in 2000 accounted for 15-20% of the total networking equipment. That is, it accounted for $7 to $10 Billion out of a $50 Billion market.
- This share increased and then slowly reduced in the recent years.

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MPLS

- The need to introduce QoS in in the IP network has led to the development of a connection-oriented architecture in the IP network, known as *Multi-protocol label switching* (MPLS)

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An MPLS connection

- The procedure is similar to ATM.
- An MPLS-enabled IP router switches IP packets not on a hop-by-hop basis using the packet's IP address. Rather, it forwards them using a label which identifies the connection that the packet has to follow.

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GMPLS

- MPLS was extended to *generalized MPLS* (GMPLS) to also include other non-packet oriented networks, such as
  - Wavelength-routed optical networks
  - Time division switching

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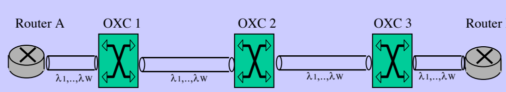
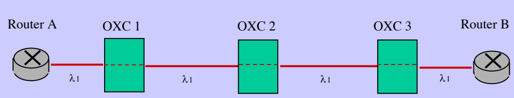
A wavelength routing optical network connection



A three-node wavelength routing network



A lightpath

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- An important feature of a wavelength routing optical network is that it is a circuit-switched network.
- A connection is an optical path through the optical network (called a *lightpath*) and it is established using a wavelength on each hop along the connection's path.

Signalling and topology reachability information

- A connection-oriented network requires a signalling protocol for setting up, maintaining, and tearing down connections in real time.
- It also requires a protocol for gathering and distributing topology reachability information.
- Examples:
  - SS7 (telephony)
  - Q.2931 (ATM)
  - OSPF, BGP, RSVP (IP)
  - LDP, CR-LDP, RSVP-TE (MPLS)

Standards Committees

- ITU-T
- ISO
- ANSI
- IEEE
- ATM Forum (now gone)
- MPLS and Frame Relay Alliance
- MFA Forum succeeded the ones above
- OIF
- IETF

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Connection-oriented networks: The ATM Architecture

Michael Devetsikiotis
ECE Department

(slides adapted from Perros and Kurose-Ross)

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Network service model

Q: What *service model* for "channel" transporting packets from sender to receiver?

service abstraction

- guaranteed bandwidth?
- preservation of inter-packet timing (no jitter)?
- loss-free delivery?
- in-order delivery?
- congestion feedback to sender?

The most important abstraction provided by network layer:

virtual circuit
or
datagram?

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Virtual circuits

"source-to-dest path behaves much like telephone circuit"
- performance-wise
- network actions along source-to-dest path

- call setup, teardown for each call *before* data can flow
- each packet carries VC identifier (not destination host ID)
- *every* router on source-dest path s maintain "state" for each passing connection
  - transport-layer connection only involved two end systems
- link, router resources (bandwidth, buffers) may be *allocated* to VC
  - to obtain circuit-like performance

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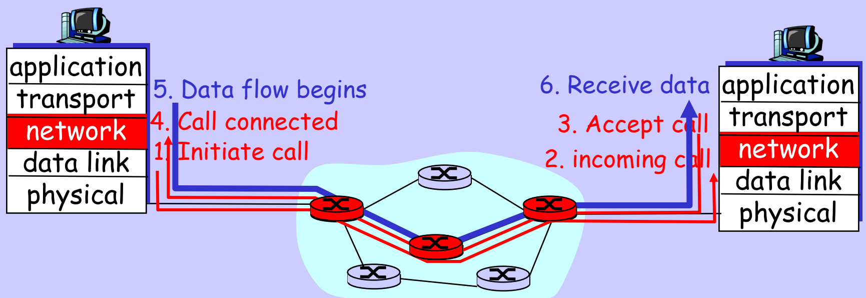
Virtual circuits: signaling protocols

- used to setup, maintain teardown VC
- used in ATM, frame-relay, X.25, MPLS



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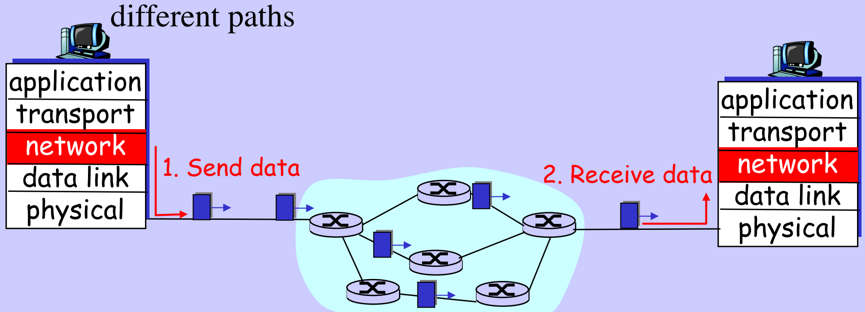
Datagram networks: the Internet model

- no call setup at network layer
- routers: no state about end-to-end connections
  - no network-level concept of "connection"
- packets typically routed using destination host ID
  - packets between same source-dest pair may take different paths



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Datagram or VC network: why?

Internet

- data exchange among computers
  - "elastic" service, no strict timing req.
- "smart" end systems (computers)
  - can adapt, perform control, error recovery
  - simple inside network, complexity at "edge"
- many link types
  - different characteristics
  - uniform service difficult

ATM

- evolved from telephony
- human conversation:
  - strict timing, reliability requirements
  - need for guaranteed service
- "dumb" end systems
  - telephones
  - complexity inside network

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ATM Layer: Virtual Circuits

- VC transport: cells carried on VC from source to dest
  - call setup, teardown for each call *before* data can flow
  - each packet carries VC identifier (not destination ID)
  - *every* switch on source-dest path maintain "state" for each passing connection
  - link, switch resources (bandwidth, buffers) may be *allocated* to VC: to get circuit-like perf.
- Permanent VCs (PVCs)
  - long lasting connections
  - typically: "permanent" route between to IP routers
- Switched VCs (SVC):
  - dynamically set up on per-call basis

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ATM VCs

- Advantages of ATM VC approach:
  – QoS performance guarantee for connection mapped to VC (bandwidth, delay, delay jitter)
- Drawbacks of ATM VC approach:
  – Inefficient support of datagram traffic
  – one PVC between each source/dest pair) does not scale (N*2 connections needed)
  – SVC introduces call setup latency, processing overhead for short lived connections

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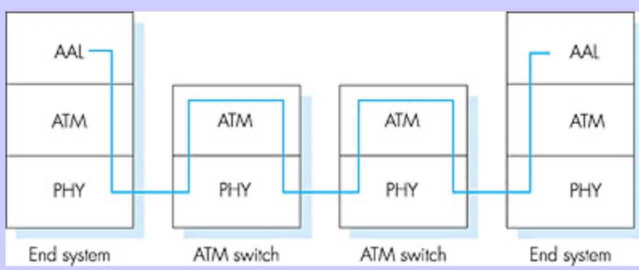
ATM architecture



- **adaptation layer: only at edge of ATM network**
  – data segmentation/reassembly
  – roughly analogous to Internet transport layer
- ATM layer: “network” layer
  – cell switching, routing
- physical layer

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The ATM Architecture

- **Basic features**
- **Why 53 bytes?**
- **The header of the cell**
- **The ATM protocol stack**
- **ATM interfaces**
- **The physical layer**

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Asynchronous Transfer Mode (ATM)

- The word *Asynchronous* in ATM is in contrast to *Synchronous* Transfer Mode (STM) that was proposed earlier on, which was based on TDM circuit-switching
- *Transfer Mode* refers to a telecommunication technique

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Asynchronous Transfer Mode: ATM

- **1980s/1990's standard for high-speed** (155Mbps to 622 Mbps and higher) *Broadband Integrated Service Digital Network* architecture
- Goal: *integrated, end-end transport of carry voice, video, data*
  - meeting timing/QoS requirements of voice, video (versus Internet best-effort model)
  - "next generation" telephony: technical roots in telephone world
  - packet-switching (fixed length packets, called "cells") using virtual circuits

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ATM was standardized by CCITT in 1988 as the transfer mode of B-ISDN

- It can carry a variety of different types of traffic, such as
  - Voice
  - Video
  - Data
- At speeds varying from fractional T1 to 2.4 and soon 10 Gbps

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- These different types of traffic have different Quality-of-Service (QoS) requirements, such as:
  - Packet loss
  - End-to-end delay

ATM, unlike IP networks, can provide each traffic connection a different type of quality of service

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Some features of ATM are…

- Packet-switching
- Connection-oriented
- Fixed cell (packet) size of 48+5 bytes
- No error protection on a link-by-link
- No flow control on a link-by-link
- Delivers cells in the order in which they were transmitted

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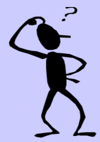

Why 53 bytes ???

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Various considerations lead to the standardization of the ATM cell

- Delay through the network
  - Transfer delay
  - Packetization delay
- Echo cancellation
- Header conversion
- Fixed vs. variable packet length

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Delay through the network

- Early ATM switches had small buffers
  - *Small packet size meant small queueing delays in ATM buffers*
- Packetization delay favors small packets
  - *Example: 64 Kbps voice transmitted in ATM cell (i.e., one byte every 125 μsec)*
  - *Packet size 16 bytes needs 16x 125 μsec=2 msec*
  - *Packet size 64 bytes needs 64x 125 μsec = 8 msec*

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- Echo cancellation
  - *Echo cancellers are needed for delays > 24 msec*
- Header conversion
  - *The longer the packet, the more time the ATM switch has to look up the header in the switching table*
- Fixed vs variable packet size
  - *Variable-size packets tend to be longer & need extra overhead*
  - *Easier to construct switches for fixed-size packets*

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The compromise...

- Europe: fixed size with 32 byte payload
- USA/Japan: fixed size with 64 byte payload
- They compromised in the middle!!

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The structure of the ATM cell

- Connections identifier:
  - VPI/VCI,
  - label swapping,
  - types of connections
- Head error control (HEC)
- Payload type indicator (PTI)
- Cell loss priority cell

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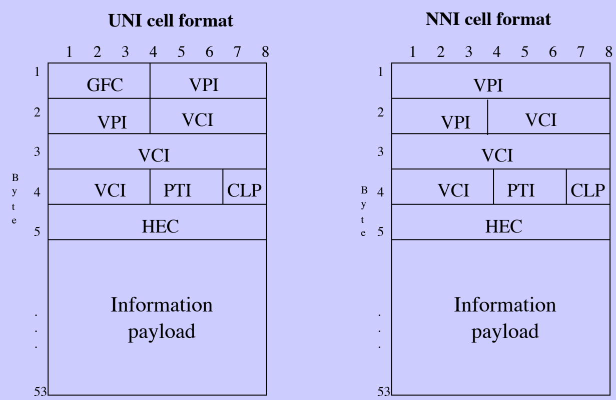
The ATM cell



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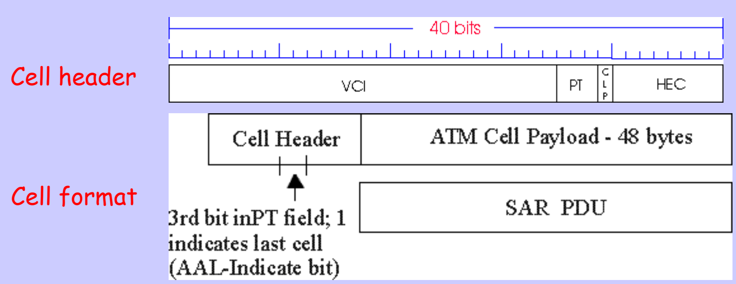
ATM Layer: ATM cell

- 5-byte ATM cell header
- 48-byte payload
  - Why? small payload -> short cell-creation delay for digitized voice
  - halfway between 32 and 64 (compromise!)



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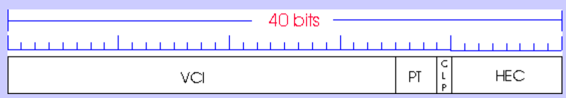
ATM cell header

- **VCI:** virtual channel ID
  – will *change* from link to link thru net
- **PT:** Payload type (e.g., RM cell versus data cell)
- **CLP:** Cell Loss Priority bit
  – CLP = 1 implies low priority cell, can be discarded if congestion
- **HEC:** Header Error Checksum
  – cyclic redundancy check



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ATM connections

- Identified by the combined fields
  – *virtual path identification* (VPI), and
  – *virtual channel identification (VCI)*
- **VPI field:**
  – 256 virtual paths at the UNI interface, and
  – 4096 virtual paths at the NNI interface.
- **VCI field:** a maximum of 65,536 VCIs.

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- VPI/VCI values have local significance. That is, they are only valid for a single hop.
- A connection over many hops, is associated with a different VPI/VCI value on each hop.
- Each switch maintains a switching table. For each connection, it keeps the incoming and outgoing VPI/VCI values and the input and output ports.

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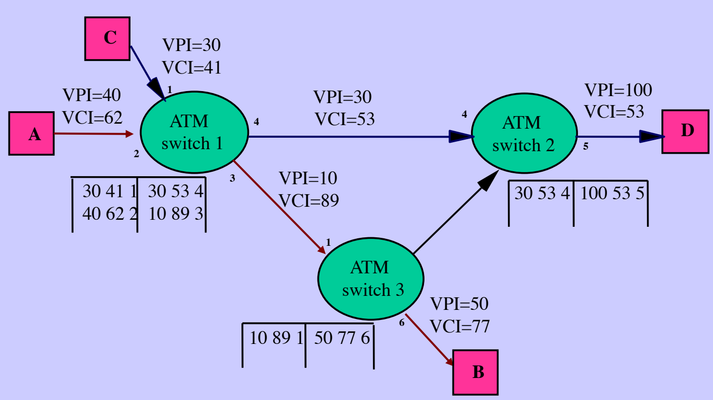
Label swapping



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PVCs and SVCs

- Depending how a connection is set-up, it may be
  - *Permanent virtual circuit (PVC)*
  - *Switched Virtual circuit (SVC)*
- PVCs are set-up administratively. They remain up for a long time.
- SVCs are set-up in real-time using ATM signaling. Their duration is arbitrary.

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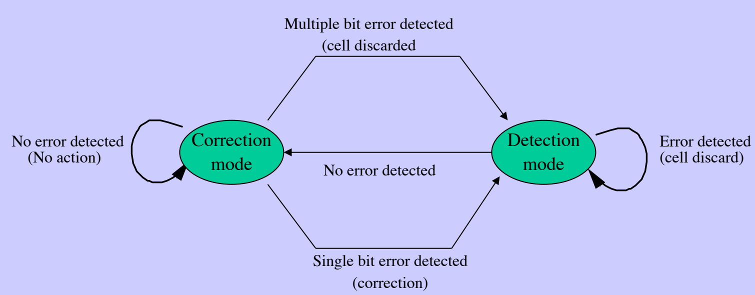
Head Error Control (HEC)



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Payload type Indicator

- **PTI Meaning**
- 000 User data cell, congestion not experienced, SDU type=0
- 001 User data cell, congestion not experienced, SDU type=1
- 010 User data cell, congestion experienced, SDU type=0
- 011 User data cell, congestion experienced, SDU type=1
- 100 Segment OAM flow-related cell
- 101 End-to-end OAM flow-related cell
- 110 RM cell
- 111 Reserved

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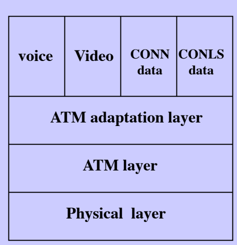
The ATM protocol stack



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ATM: network or link layer?

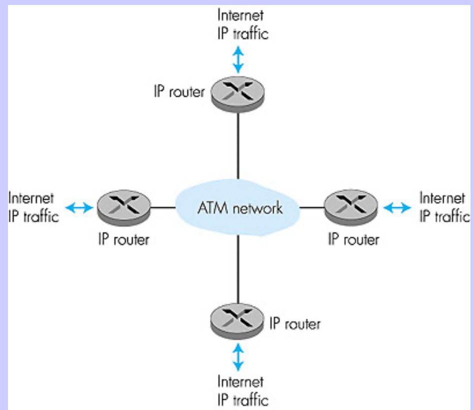
Vision: end-to-end transport: "ATM from desktop to desktop"

– ATM *is* a network technology

Reality: used to connect IP backbone routers

– "IP over ATM"

– ATM as switched link layer, connecting IP routers



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Layer 1: The physical layer

- The physical layer transports ATM cells between two adjacent ATM layers.
- It is subdivided into
  – *transmission convergence* (TC) sublayer
  – *physical medium-dependent* (PMD) sublayer.

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Layer 2: The ATM layer

- The ATM layer is concerned with the end-to-end transfer of information, i.e., from the transmitting end-device to the receiving end-device.
- Below, we summarize its main features.

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Connection-oriented packet switching

The ATM layer is a connection-oriented ***point-to point*** packet-switched network.

- A connection is identified by a series of VPI/VCI labels, as explained above, and it may be point-to-point or point-to-multipoint.
- Cells are delivered to the destination in the order in which they were transmitted.

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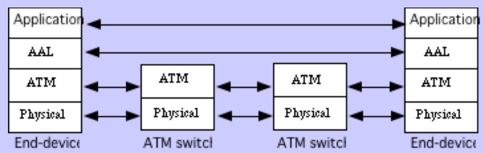
Cell switching in ATM networks
is carried out at the ATM level



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No error and flow control on each hop

- Low probability of a cell getting lost or delivered to the destination end-device in error.
- The recovery of the data carried by lost or corrupted cells is expected to be carried out by a higher-level protocol, such as TCP.
- When TCP/IP runs over ATM, the loss or corruption of the payload of a single cell results in the retransmission of an entire TCP PDU.

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Addressing

- Each ATM end-device and ATM switch has a unique ATM address.
- Private and public networks use different ATM addresses. Public networks use E.164 addresses and private networks use the OSI NSAP format.
- ATM addresses are different to IP addresses.

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Quality of service

- Each ATM connection is associated with a quality-of-service category.
- Each quality-of-service category is associated with a set of traffic parameters and a set of quality-of-service parameters.
- The ATM network guarantees the negotiated quality-of-service for each connection.

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Congestion control

- In ATM networks, congestion control permits the network operator to carry as much traffic as possible without affecting the quality of service requested by the users.
- It consists of *call admission control* and a *policing mechanism*.

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Layer 3: The ATM adaptation layer

- The purpose of AAL is to isolate higher layers from the specific characteristics of the ATM layer.
- AAL consists of the
  - *convergence* sublayer, and the
  - *segmentation-and-reassembly* sublayer.

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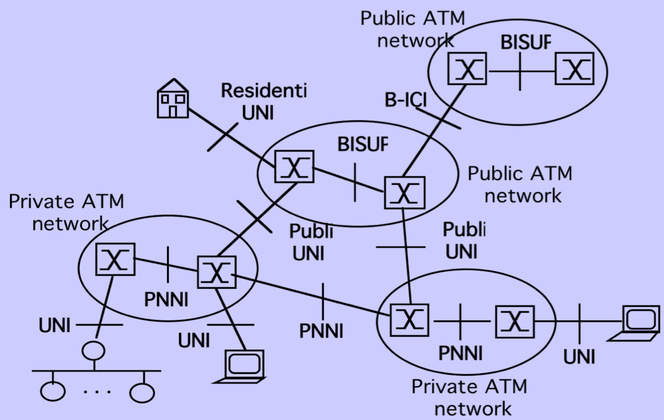
ATM interfaces



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ATM Physical Layer

Two pieces (sublayers) of physical layer:

- Transmission Convergence Sublayer (TCS): adapts ATM layer above to PMD sublayer below
- Physical Medium Dependent: depends on physical medium being used

TCS Functions:

- Header **checksum** generation: 8 bits CRC
- Cell **delineation**
- With "unstructured" PMD sublayer, transmission of **idle cells** when no data cells to send

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ATM Physical Layer (more)

Physical Medium Dependent (PMD) sublayer

- **SONET/SDH**: transmission frame structure (like a container carrying bits);
  - bit synchronization;
  - bandwidth partitions (TDM);
  - several speeds: OC1 = 51.84 Mbps; OC3 = 155.52 Mbps; OC12 = 622.08 Mbps
- **TI/T3**: transmission frame structure (old telephone hierarchy): 1.5 Mbps/ 45 Mbps
- **unstructured**: just cells (busy/idle)

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The physical layer

- Transmission convergence (TC) sublayer
  - *HEC cell generation and verification*
  - *Decoupling of cell rate*
  - *Cell delineation*
  - *Transmission frame generation and recovery*
- Physical medium dependent (PMD)
  - *Timing function*
  - *Encoding/decoding*

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The transmission convergence (TC) sublayer

- *HEC cell generation and verification*
  - Implements the HEC state machine
- *Decoupling of cell rate*
  - Maintains a continuous bit stream by inserting idle cells
- *Transmission frame generation and recovery*
  - Such as SONET frames

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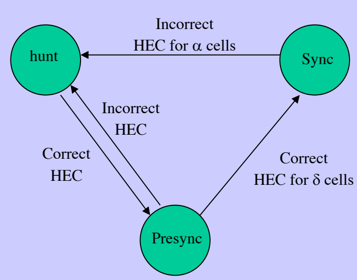
Cell delineation

is the extraction of cells from the bit stream received from the PMD sublayer.



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ATM physical layer interfaces

- *SONET/SDH*
- *Plesiochronous digital hierarchy (PDH)*
- *Nx64 Kbps*
- *Inverse mulitplexing for ATM (IMA)*
- *asymmetric digital subscriber line (ADSL)*
- *TAXI (FDDI)*
- *ATM 25*

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The SONET/SDH hierarchy

Optical level	SDH equivalent	SONET level (electrical)	Data rate (Mbps)	Overhead rate (Mbps)	Payload rate (Mbps)
OC-1	-	STS-1	51.840	1.728	50.112
OC-3	**STM-1**	**STS-3**	**155.520**	**5.184**	**150.336**
OC-9	STM-3	STS-9	466.560	15.552	451.008
OC-12	**STM-4**	**STS-12**	**622.080**	**20.736**	**601.344**
OC-18	STM-6	STS-18	933.120	31.104	902.016
OC-24	STM-8	STS-24	1244.160	41.472	1202.688
OC-36	STM-12	STS-36	1866.240	62.208	1804.932
OC-48	**STM-16**	**STS-48**	**2488.320**	**82.944**	**2405.376**
OC-96	STM-32	STS-96	4976.640	165.888	4810.752
OC-192	**STM-64**	**STS-192**	**9953.280**	**331.776**	**9621.504**
OC-768	**STM-256**	**STS-768**	**39813.120**	**1327.104**	**38486.016**
OC-N	STM-N/3	STS-N	N*51.840	N1.728	N*50.112

- **Products are only available for levels indicated in bold**

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